# Optimum lime content identification for lime-stabilised rammed earth

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**Abstract**

The rising price of energy and a recognition of the human impact on climate change has resulted in growing interest in environmentally-friendly construction techniques such as rammed earth. Modern rammed earth is generally stabilised with small quantities of Portland cement in order to improve its strength and durability, however an alternative is to use lime to stabilise the raw soil. This is common practice in road construction, for example, but is less common in RE. This paper presents experimental results illustrating the existence of an optimum lime content that maximises the unconfined compressive strength and stiffness of an engineered lime-stabilised rammed earth and the experimental procedures employed to determine it. The effect of curing regime (oven as opposed to natural drying) on the final unconfined compressive strength of the material was also investigated. An optimum lime content for the tested soil has been identified and several methods to determine its rough value presented which have the potential to reduce testing times and so associated costs.

*Keywords:* Lime stabilisation, rammed earth, unconfined compressive strength, optimum lime content.

## 1. Introduction

Climate change, growing energy costs and the impact of human activities on the environment have all become key concerns for future development in recent years. As construction processes required to develop infrastructure constitute major sources of carbon dioxide production and energy consumption, alternative methods are beginning to be explored in order to reduce their environmental impact. One such method is rammed earth (RE) construction.

RE is an ancient building technique which utilises moist, sandy-loam (USDA classification) subsoil compacted into formwork to form strong, durable and free-standing structures [16, 20]. While the technique has changed little since its inception, it is now common to stabilise RE materials with small quantities of Portland cement in order to improve its strength and durability. The incorporation of Portland cement, however, seems to reduce the sustainability of RE and increases both its cost and environmental impact [8, 28]. Although a comparative analysis of the sustainability of lime versus that of Portland cement in terms of their thermal and embodied energy finds conflicting results in the literature [28, 36], depending on the mineralogy of the

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clay, availability and transportation, lime stabilisation can represent a more efficient solution than Portland cement for the improvements of the material mechanical properties (it is well established that using Portland cement to stabilise clayey soils does not always produce the expected enhancements in terms of material performance). In Australia, the cost of lime and Portland cement is fairly similar.

The interaction between lime and soil has been studied by several authors and it is quite understood that lime stabilisation improves the strength, stiffness, plasticity/workability and water adsorption of the raw soil [13, 14]. The lime-soil reaction can be described by three general phenomena: *i)* cation exchange, *ii)* pozzolanic reaction and *iii)* carbonation. Cation exchange takes place as soon as lime is added to soil in the presence of water. This reaction produces free $Ca^{++}$ ions and leads to an increase in the pH of the soil-lime mix. pHs above roughly 12.4 (the pH of lime-saturated water), achieved through significant lime addition, encourage the solubility of silica and alumina present in the clay minerals and quartz [4]. The silica and alumina then react with the $Ca^{++}$ to form calcium silicates and aluminates. From here on, in the presence of water, the reaction is very similar to the Portland cement hydration process: calcium silicates become hydrates and form cementitious compounds. This pozzolanic reaction is exothermic and temperature dependent, with the rate increasing at higher temperatures. It is understood that the pozzolanic reaction is affected by soil mineralogy and that the hydration process might take place over a long period, potentially producing continuous

strength development for periods longer than the standard 28-day hydration time for Portland cement concrete (for instance). The formation of cementing agents (mainly the products of silica hydrates) is assumed to be the main source of strength improvement in lime-stabilised soils [34].

Carbonation is another lime-soil reaction that happens when lime reacts with carbon dioxide present in the air, mostly associated with hot-dry climates where control of curing is difficult. It is a phenomenon that should be avoided because it inhibits the formation of cementitious products that hence weakens the material strength. However, it has been shown that this effect can be effectively mitigated through the proper design and control of stabilisation regime and curing conditions [2].

Although several examples of historical lime-stabilised RE (LSRE) structures survive to this day, the use of lime in the earthen building construction industry has not been exhaustively investigated so far [7]. This papers aims to understand whether an Optimum Lime Content (OLC) that maximises the Unconfined Compressive Strength (UCS) of a given soil mixture exists for RE materials and outlines an experimental procedure for its determination. The effect of lime stabilisation on the stiffnesses of these materials is also investigated in order to better characterise its elastic behaviour. The details of the experimental programme used in this study are illustrated in Section 2 and findings are extensively discussed in Section 3. The suitability of those procedures used to approximately identify the OLC for an RE soil are discussed in Section 4 and subsequent observations and recommendations

provided at the end of this paper in Section 5.

## 2. Experimental procedure

An engineered soil was prepared by combining known quantities of kaolin clay powder, silica flour, sand and gravel, following guidelines available in RE literature [7, 18, 27, 37]. The choice of using an engineered soil mixture was desirable due to the need to control material grading and mineralogy for testing. Individual component quantities were determined following recommendations made by Houben and Guillaud [20] for the selection of a suitable soil for RE construction, with the final Particle Size Distribution (PSD) shown in Figure 1. The gravel component was sieved to pass a 10 mm sieve.

Unstabilised RE materials are compacted at their optimum water content (OWC) in order to ensure the highest dry density and, by extension, strength [22]. This practice is also used for stabilised RE materials. For Portland cement stabilisation, the maximum amount of cement that can be added to stabilise the soil then becomes strictly related to the compaction OWC: it would be inefficient to increase the cement content if there was not enough water to hydrate it. Water also plays a critical role in the stabilisation process of lime-stabilised RE materials, as was discussed in the previous Section. In this study, the initial water content, that is the water content at time of mixing and moulding of the specimens, was also taken as equal to the compaction OWC. This choice is motivated by the fact that rammed earth materials are always nominally compacted at their OWC during con-

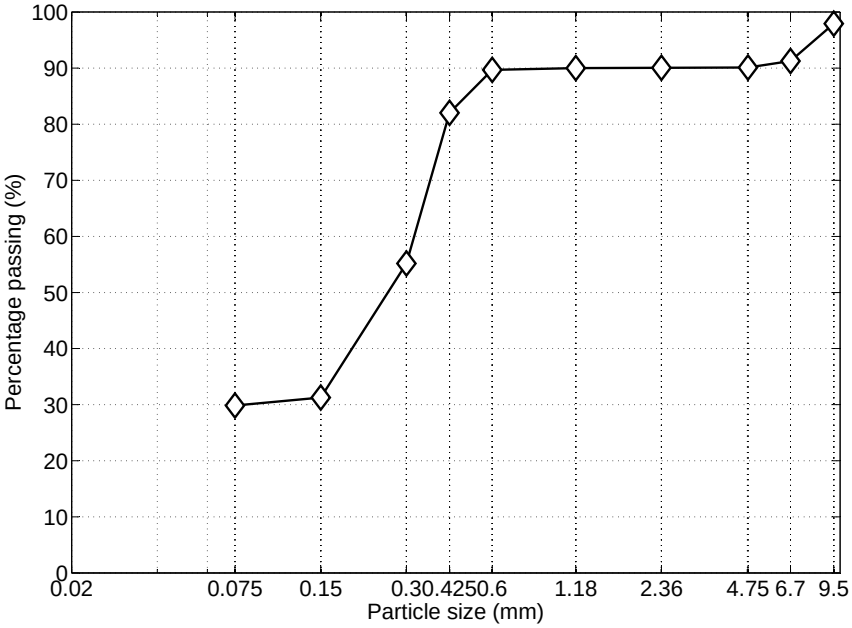


Figure 1: Particle size distribution of engineered soil mixture used in the experimental programme.

struction and it would be both unrealistic and impractical to use moulding water contents different from it. The assessment of stabilised soil mixes with other than optimum initial water contents is therefore beyond the purpose of this paper, but is discussed elsewhere [11, 12]. The focus of this investigation is on the existence of an OLC for a soil mixture with a fixed amount of clay. Although the strength and stiffness of compacted lime-stabilised soils depend on many other factors (mineralogy, curing temperature, relative humidity and duration, for example), those factors were set constant in all tests performed in this study in order to obtain results that were only lime-content

dependent.

### *2.1. Determination of optimum water contents*

Laboratory determination of the OWC is generally carried out using either the Standard or the Modified Proctor Test (MPT) [31]. The MPT has a compactive effort very similar to that used on-site and is a well specified, codified and widely established test and hence repeatable in any laboratory. For these reasons, the MPT was used in this study.

The MPT for the unstabilised material was performed according to AS 1289.3.2.1-2009. Oven-dried (for 24 hours at 105°C) soil mix was wetted with water and left to equilibrate for 7 days in sealed containers, in order to ensure a uniform water content, $w\%$, prior to compaction testing. After compaction, the samples were dried in an oven at 105°C to measure $w\%$ and so dry density. The procedure was repeated for different values of $w\%$ and the OWC was found as the water content corresponding to the maximum dry density $\rho_{d,max}$ achieved.

For the lime-stabilised material, the procedure specified by AS 1289.3.2.1-2009 was slightly modified. Oven-dried soil material was combined with a selected quantity of hydrated lime and dry-mixed thoroughly for a minimum of five minutes. Then, batches were made with known values of $w\%$. As the addition of water initiates the cation exchange, flocculation and pozzolanic reactions, compaction was completed within 45 minutes of wetting in order to prevent undesired soil fabric changes from interfering with the test. Un-

like for unstabilised materials, oven drying could not then be used to verify the material water content due to the loss of (non-evaporable) water via the above-mentioned reactions triggered by the high drying temperatures. Material water content was therefore taken to be the added water content $w\%$ used during compaction and the OWC determined as described above. The OWC, water/lime ratio ($w/L$) and $\rho_{d,max}$ for each of the investigated lime contents are given in Table 1. Note that lime and water contents are given as a percentage of the dry soil mass (i.e. not inclusive of the lime mass).

Table 1: Lime content, OWC, $\rho_{d,max}$ and water/lime ratio results

| Lime content (%) | 0 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| OWC (%) | 7.6 | 7.7 | 8.1 | 8.0 | 9.6 | 8.5 |
| $w/L$ ratio | N/A | 3.85 | 2.70 | 2.00 | 1.92 | 1.42 |
| $\rho_{d,max}$ (kg/m$^3$) | 2190 | 2130 | 2070 | 2140 | 2060 | 2030 |

### *2.2. UCS specimen preparation*

Material UCS is generally used to assess stabiliser effectiveness [27, 30, 38]. UCS was determined for 100-mm diameter, 200-mm high cylindrical specimens tested in uniaxial compression between Teflon sheets [9]. Five specimens were prepared per lime content, prepared following the same mixing and compaction procedures used for OWC testing. Specimens were carefully extracted from the mould immediately following manufacture and transferred to wire racks to cure for 28 days under constant conditions of 94±2% relative humidity (RH) and 21±1°C. It is important to note that this allowed

specimen water contents to reduce with time. That being said, it is beyond the purposes of this study to investigate the effect of the water content at testing on the compressive strength. The aim of this paper is to discover whether, for an initial water content equal to the OWC and under fixed curing conditions, samples made of the same soil but different lime contents show an OLC that maximizes the compressive strength. The curing time prior to testing was set to 28 days following the recommendations of AS 5101.4 [32] and other Australian guidelines for lime stabilisation practices [1]. These curing conditions might not have represented those on-site, but allowed for the repeatability of the procedure to be assessed in a systematic manner. These specimens are hereafter referred to as "A-series" specimens.

For many years and due to the lack of proper standards, stabilised earthen materials have been viewed and treated as weak forms of concrete. As a consequence, no distinction is commonly made between the strengths obtained from specimens tested under saturated, ambient or oven-dry conditions (for example as in Walker and Standards Australia [37]). However, given the strong relationship between water content, suction and strength (well established for earthen construction materials), such distinction must be considered as recently confirmed in several studies [3, 10, 22]. Furthermore, the temperature-dependent nature of the lime stabilisation process indicates that the performance of specimens tested at ambient conditions will be different to those of oven-dried specimens [17]. For this reason, additional specimens were manufactured (using the same procedures discussed above) and allowed

to cure under identical conditions to A-series specimens for 28 days before being oven-dried at 105°C for additional 24 hours prior to UCS testing. These are hereafter referred to as "O-series" specimens. Again, five specimens were tested per lime content.

## 3. Results and discussion

### *3.1. Effect of curing conditions on 28-day UCS*

Results from UCS testing on A– and O-series specimens are shown in Figure 2 in terms of mean UCS values and standard deviations ($s$) (error bars denote $\pm 1s$). Figure 2 shows that a significant increase in mean UCS occurs between A– and O-series specimens. For unstabilised material (i.e. 0% lime content), it is well understood that this increase is due to a significant increase in total suction on oven drying to a lower water content [3, 22]. For the stabilised samples, the reasons behind the increase in strength are less straightforward.

One reason relates to the temperature effect; it is well established that the formation of pozzolanic compounds in lime-stabilised soils depends on temperature [17, 35]. Curing time is another factor that significantly affects the strength of soil-lime mixtures. Croft [14], and later Consoli et al. [11], presented results for the UCS of lime-stabilised soils as affected by curing time. Unlike cement-stabilised soils and concrete, which achieve UCSs approaching their mature values after 4 weeks, these authors demonstrated that curing times between 7 and 60 weeks might be required for lime-stabilised

soils to reach maturity, depending on soil mineralogy, stabiliser content and compaction water content. Therefore, the pozzolanic reaction after 4 weeks might be incomplete for materials tested in this study. The significant increase in O-series UCS might therefore be attributed to a combination of increased suction, as mentioned above, and also to a dramatic acceleration of the pozzolanic reaction on exposure to elevated temperatures. All other factors being the same, the higher the curing temperature, the greater the extent of the pozzolanic reaction (and, by extension, strength) that can be induced in a soil-lime mixture [35].

Figure 2 shows that, in some cases, values of $s$ increased dramatically between A– and O-series specimens. Given the severity of the oven drying process, it might be that, had specimens been constantly wetted during the 24 hours in the oven, less scatter (i.e. lower values of $s$) would have been observed in the O-series results despite the higher temperatures. In contrast, the A-series samples were exposed to a highly humid environment for 28 days, allowing the hydration process to happen more uniformly and thus producing more consistent results.

Results given in Figure 2 therefore suggest that ambient and oven-dried specimens should not be assessed in the same way nor should their results be indistinctively used for the same purpose. Instead, specimens should be tested under conditions representative of those likely to be encountered during their lifetime for UCS determination [3]. Results for O-series specimens will therefore no longer be used in this paper to investigate LSRE properties.

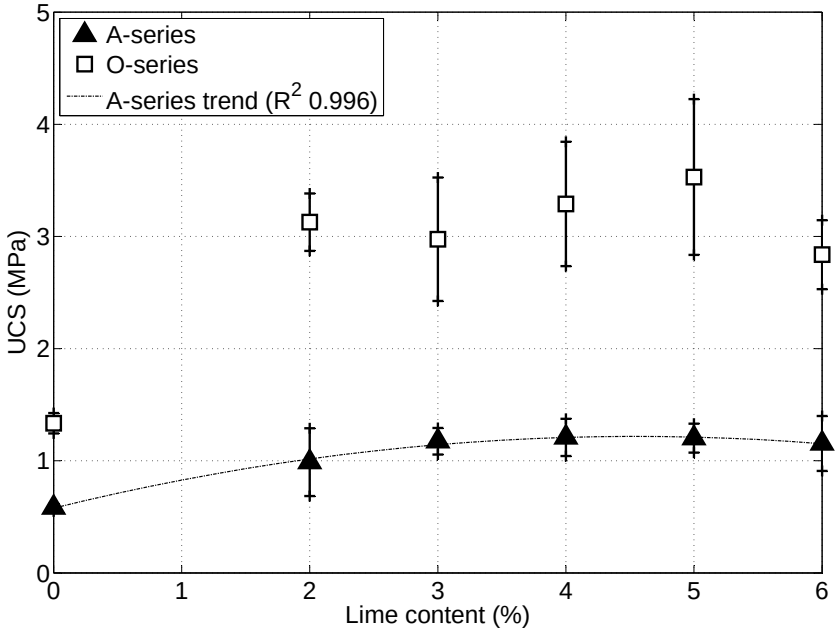


Figure 2: UCS results in terms of mean values and standard variation for (Ambient) A- and (Oven-dried) O-series specimens.

### *3.2. Effect of lime and water content on 28-day UCS*

As shown in Figure 2, 28-day UCS values increase with increasing lime content up to an "Optimum Lime Content" (OLC) around 4%, above which no additional beneficial changes in UCS are observed. A similar trend to that found for A-series specimens shown in Figure 2 was also found by Bell [4], who demonstrated that this phenomenon was due to the limited amount of water available to hydrate the amount of lime, so that the material was effectively "lime saturated" for lime contents above the OLC; this is discussed in more detail later in this paper. It might be worth to notice again that, as

mentioned in the previous section, specimens tested in this study were not sealed following manufacture but were instead allowed to cure in a highly humid environment. For this reason, the water content at 28 days at testing is different to the initial water content at mixing. It is beyond the purposes of this study to investigate the effect of the water content at testing on the compressive strength.

In another study [29], UCSs were determined for unfired soil bricks manufactured using two Botswanan soils (*Mahalapye* soil, clay soil (48.0% clay) and *Tsabong* soil, sandy loam (14.5% clay) (USDA classifications)) stabilised with a range of lime contents from 5% to 15%. An OLC was not identified for those soils, with UCS values instead increasing as long as the lime content increased. It is difficult to draw any conclusions on the comparison between Ngowi's results and those presented here, however, due to the substantial differences in compaction regime, significantly higher clay contents of those materials tested and the lack of extra data in Ngowi's work, for example on clay mineralogy and the moulding water content used. The lack of a distinct OLC in Ngowi's work therefore does not invalidate the finding of an OLC for the material tested in this study.

Some previous studies on lime-stabilisation of silt [12] indicated the initial porosity/lime ($n/L$) ratio as a crucial parameter to evaluate the effectiveness of lime stabilisation. It was found that the UCS decreased with increasing $n/L$ for specimens manufactured and maintained at a constant amount of water (equal to 20% of the soil weight) with varying amount of lime and dry

unit weights. These conditions (constant water and varying dry unit weight), however, imply that the compactive effort was not the same for all specimens. In the study presented here, however, all specimens were manufactured using the same compactive effort but at water contents equal to their OWC, which varied with lime content.

Figure 3 presents A-series UCS vs. $n/L$ where $n$ has been calculated assuming a specific gravity value of 2.65 for all material lime contents. Unlike results found in Consoli et al., results shown in Figure 3 seem to display a peak UCS vs. $n/L$ value corresponding to lime contents of between 3 and 4%, similar to results shown in Figure 2 for the OLC. The lack of a strong agreement between the results of this study and those in Consoli et al. can again be attributed to factors such as different compaction energy, soil composition and curing regime. In addition, samples in Consoli et al. had constant but higher water contents (constant 20% of soil mass) than those used in this work (between 7.6 and 9.6%) that guaranteed the hydration of the lime present in the soil (between 3 and 9%) and were tested at higher $n/L$ values as found in this study. These results would therefore suggest that a universal relationship between $n/L$ and UCS cannot be derived; however, within the confines of the material tested here, results for $n/L$ might offer some indication as to the location of the OLC. Clearly, this requires further testing in order to be substantiated.

One last observation might be made regarding the effect of carbonation. In a study on carbonation of stabilised soil-lime mixtures [2] it was found

that an increase in the amount of air voids present in a sample increases the level of carbon dioxide that penetrates the soil. Unsealed samples cured in an environment with 20°C and relative humidity of 100% showed no significant loss of strength at 28 days as compared to the strength of sealed (hence no carbonation allowed) samples. For the unsealed samples, water present in the pores reduced carbon dioxide ingress and hence diminished the carbonation process. Other samples exposed to higher temperatures (40°C) during the same curing period showed an important loss of strength gain due to the loss of water in the pores (i.e. an increase of air voids) that facilitated carbonation. Since all specimens in this study were cured for a set time in a curing room with a high relative humidity of 94% and a low temperature of 20°C, it is assumed that carbonation did not play a major role in the evolution of material strength.

### *3.3. Effect of lime stabilisation on stiffness*

Material stiffness plays an important role in the prediction of structural displacements and also in the structural analysis of composite elements (like reinforced earth). This latter case became evident over recent years following the destruction of the adobe town of Bam in Iran (A UNESCO World Heritage site) during the December 2003 earthquake, which was accompanied by a severe loss of life. A study (unpublished) conducted after the disaster showed the inappropriate use of steel beams to reinforce the existing buildings during conservation work prior to the earthquake. The beams were far

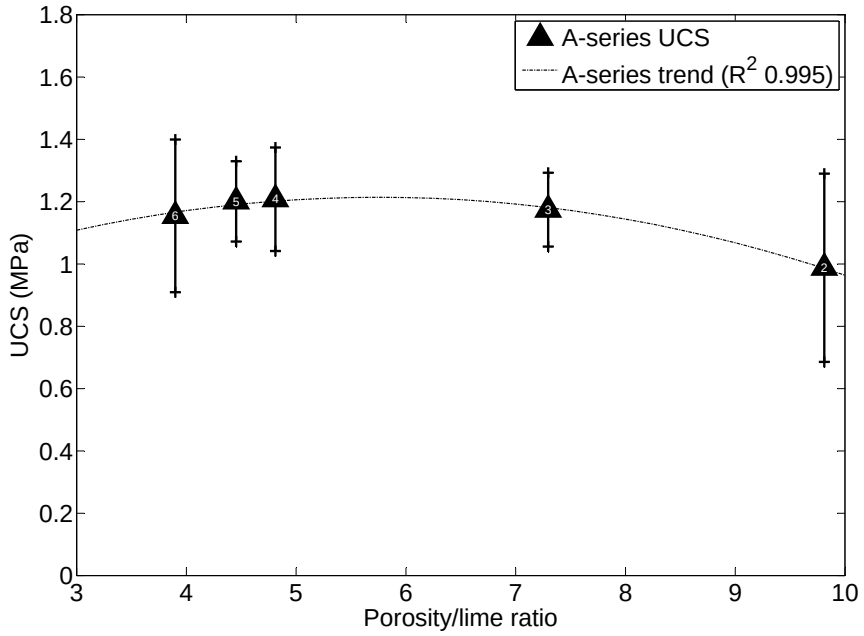


Figure 3: UCS versus initial porosity/lime ratio. The numbers inside the markers indicate the lime content in %.

too stiff (E=205 GPa) with respect to the adobe material (E=85 MPa) and the two elements (the steel beam and the adobe wall in which the beam was embedded) acted separately during the earthquake, with the wall crushing and the steel beam not taking any load. The same study showed that the use of polypropylene bars (with lower stiffness E=850 MPa) as tensile elements grouted in the wall improved the seismic performances. This example illustrates the motivations behind evaluating the stiffness of RE in this study.

UCS specimens were tested between Teflon sheets to reduce confinement effects, following the work of Ciancio and Gibbings [9]. Thus, the displacement between the loading platens divided by the height of the sample could be regarded as the true axial deformation. Figure 4 shows the uniaxial compressive stress-strain $\sigma - \varepsilon$ curves for A-series specimens tested in this work (again, five specimens per lime content). The initial segment of the curves, for very low values of stress, is characterised by a shallow slope due to any re-alignment of the loading plates required to fully contact the specimen surfaces. Once the load is uniformly applied, the slope of the stress-strain curve increases to a maximum value before decreasing again. The tangent slope of the $\sigma - \varepsilon$ curve represents the tangent stiffness of the material, the maximum value of which is hereafter designated $E_0$.

Mean values of $E_0$ calculated for each group of specimens with the same lime content are shown in Figure 5. These results suggest that $E_0$ significantly increases with the initial addition of lime (i.e. between 0 and 2% lime content) and then reaches a peak value of approximately 200 MPa at 4% lime content,

corresponding well to the OLC already identified for specimen UCS. Again, this behaviour may be due to increasing rates of the lime-soil pozzolanic reaction up to the point of lime saturation, whereupon the reaction rate becomes stable [19].

It is important to state that $E_0$ does not coincide with the Young's modulus $E$ of the material. The latter characterises the initial elastic relationship between normal stress $\sigma$ and strain $\epsilon$, the former the incremental (and not necessarily elastic) relationship between $\sigma$ and $\epsilon$. With this difference in mind, a comparison is provided between the $E_0$ values obtained in this work and the recommended values of Young's modulus available in the literature. From Table 2 it can be seen that $E_0$ stiffnesses for lime-stabilised materials given here fit well within the upper range expected for unstabilised RE Young's modulus. A significant difference is seen, however, between values of the stiffness for lime-stabilised and cement-stabilised RE.

In the absence of experimental data, Walker and Standards Australia [37] recommend the use of a Young's modulus equal to 500 MPa for all RE materials, regardless of the use of stabiliser employed. This value seems to overestimate the data obtained in this study and by others in the available literature, so that values of $E$ lower than 500 MPa would seem to be more suitable for unstabilised and lime-stabilised materials. A more flexible method to predict $E$ is provided in NZS 4297:1998, whereby $E = 300 \times f'_c$, where $f'_c$ is the material characteristic compressive strength ($f'_c = 1 - 1.5x_1 \left(\frac{s}{\mu}\right)$, where $s$ and $\mu$ are the standard deviation and average of the series UCS and $x_1$ is the

lowest series UCS result). The experimental values found in this work for $E_0$ and $f'_c$ are given in Table 3 alongside predicted values calculated using NZS 4297:1998. Results given in Table 3 indicate that the method proposed by NZS 4297:1998 is able to estimate the order of magnitude of the stiffness of the material, provided that $f'_c$ has been accurately obtained. It should be noted that, as the calculation of $f'_c$ depends on the mean and standard deviation of a tested series, the testing of a larger number of specimens might improve the match between predicted and experimental values. However, it is the authors' opinion that a single mathematical formulation to predict an accurate value of $E$ from $f'_c$ for LSRE would be difficult (if not impossible) to implement due to the high variability of existing soils and factors affecting their strengths and stiffnesses, so that preference should always be given to experimentally determined stiffness values.

Table 2: Stiffness values as reported by other authors and in this work for URE, LSRE (lime content in %) and CSRE (cement content in %).

| Material type | Stiffness (MPa) | Author |
|---|---|---|
| URE | 205 | Maniatidis et al. [26] |
| URE | 160 | Maniatidis and Walker [25] |
| URE | 160 | Jaquin [21] |
| URE | 75 | Bui and Morel [5] |
| URE | 95 | This work |
| LSRE (2–6) | 160–227 | This work |
| CSRE (6–10) | 500 | Jayasinghe and Kamaladasa [24] |

Table 3: Relationship between $E_0$ found in this work and $E$ as recommended by NZS 4297:1998 for A-series specimens

| | Lime content (%) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 2 | 3 | 4 | 5 | 6 |
| $f'_c$ (MPa) | 0.49 | 0.40 | 0.82 | 0.73 | 0.86 | 0.64 |
| $E_0$ (MPa) | 95 | 160 | 196 | 227 | 172 | 204 |
| $E$ (MPa) as per NZS [30] | 147 | 120 | 246 | 219 | 258 | 192 |

## 4. Methods to identify the OLC

The existence of an OLC is a well known concept extensively applied in the lime stabilisation of soils used in road-building, for example, however it is a less well understood concept for RE applications. Results presented in this paper indicate the existence of an OLC value, for those materials tested, that allows for maximum material performance with the minimum use of lime. A common procedure used by RE practitioners to identify the OLC would be similar to the one presented in this paper, i.e. to manufacture several specimens with different lime content, to measure their UCS and finally to select the lime content that produces the maximum strength. There is no doubt that this procedure is time consuming and requires the fabrication of many specimens. Eades and Grim [15] and Hilt and Davidson [19] suggested alternative methods to more quickly identify the OLC:

- *Eades and Grim [15]:* 20g of stabilised soil sieved to pass 425$\mu$m is mixed with 100mL of distilled water and shaken for 30 seconds, and then for another 30 seconds every 10 minutes for a total of one hour. The pH of the resulting slurry is then tested with a pH meter calibrated

to a pH 12 buffer solution. The OLC corresponds to the lime content required to produce a soil water pH of 12.4, lime saturated solution. Although tests are conducted on the fine fraction of the stabilised material, i.e. that fraction most reactive to lime stabilisation, results are assumed to apply to the entire material grading.

- *Hilt and Davidson [19]* Stabilised soil, again sieved to pass 425$\mu$m, is wetted and allowed to cure for 24 hours prior to plastic limit (PL) testing as per AS 1289.3.2.1-2009 [33]. The OLC corresponds to the lime content above which no further change in PL occurs. Again, it is assumed that tests conducted on the fine soil fraction apply to the entire material grading.

Figure 6 shows results for plastic limit and pH testing as compared to results found for UCS testing for material stabilised to the range of lime contents used in this study. Note that results for pH at a lime content of 0% are not shown for clarity. Figure 6 shows that OLCs determined using the pH and PL methods show good agreement with the OLC of 4% previously identified through UCS testing (pH=12.4 at 3.5% lime content whilst PL becomes roughly constant above 4% lime content). Results given in Figure 6 also support those observations made in the previous section that soils prepared to lime contents $< 4\%$ had insufficient lime to saturate the pore water, such that its capacity to dissolve the soil minerals into calcium silicates is reduced, as these materials have pH environments less than the 12.4 limit

and so a reduced ability to dissolve the soil minerals into calcium silicates and aluminates. The water is, however, sufficient to hydrate all calcium silicate products but the hydration process is not enough to mobilise the maximum strength of the material. On the other hand, materials prepared to lime contents above 4% had sufficient lime to saturate the pore water, as shown by pH conditions $> 12.4$, but lacked sufficient water to fully hydrate the available lime (as indicated by reducing $w/L$ values with increasing lime content in Table 1). The pozzolanic reaction in this case is governed by the availability of water and not by the lime content, resulting in the production of similar amounts of cementitious compounds for specimens of $> 4\%$ lime content and, hence, similar compressive strengths at 28 days curing time.

For the materials tested in this work, the agreement between OLCs determined via pH, PL and UCS testing therefore indicates that pH and PL tests are both suitable for determining the approximate value of the OLC of an RE material. This conclusion, however, requires further testing to be fully substantiated (for example the use of additional soil types, curing conditions etc.). If proved to be reliable for RE, the *Eades and Grim* and *Hilt and Davidson* tests could easily be performed to identify the rough location of the OLC, so that the range of lime contents, and so testing time and costs, required for confirmative UCS testing can be significantly reduced.

## 5. Conclusions

This paper has presented a series of tests investigating the existence of an optimum lime content that maximises the compressive strength of a lime-stabilised RE material. The tests produced several key findings:

- an OLC was found for the studied soil mixture such that, for a given curing time, clay content and optimum water content at moulding (as determined by the MPT), no beneficial change to strength or stiffness is noticed with increased lime content;

- exposure of specimens to elevated temperatures resulted in a significant increase (more than double the results of the A-series) of the UCS at 28 days;

- the formula $E = 300 \times f'_c$ proposed by NZS 4297:1998 seemed to be appropriate for predicting the order of magnitude of the stiffness of LSRE. It is therefore recommended when rigorous lab procedures for the determination of the material stiffness are not available. The generic value of $E = 500$ MPa proposed by Walker and Standards Australia [37], however, overestimates the values found in this work for URE and LSRE;

- a close agreement was found between UCS, PL and pH testing for identification of the OLC.

It has been shown that the use of oven-dry conditions for UCS testing results in a significant overestimation of the material UCS. Specimens should therefore be tested under conditions similar to those to which they will be exposed during their lifetime if an accurate assessment of their UCS is to be made.

An OLC of 4% was found for the tested soil, above which no beneficial change in UCS or stiffness was found with increasing lime content for the testing conditions used. Subsequent pH testing suggested that this was due to the lime saturation of the pore water for lime contents above 4%.

Given its lengthy duration, alternative testing methods to UCS testing were investigated for OLC determination and a close agreement was found between OLCs determined by UCS, PL and pH testing. Both pH and PL testing might therefore offer suitable alternatives to extensive and time consuming UCS testing for more rapidly determining the OLC, which might, in turn, offer significant cost savings to RE contractors.

It is important to stress, however, that results discussed in this work are for a single soil type and that other factors, such as curing time, lime type, curing temperature and water content at testing, should also be taken into account before any general rule for lime stabilisation could be determined. It would be inappropriate to extrapolate a general rule valid for any type of soil from those results presented here. Further investigations are then necessary to draw more general conclusions on this subject.

## 6. Acknowledgments

The first two authors would like to thank the Australian Research Council and the Western Australia Department of Housing for providing the funding necessary to complete this work.

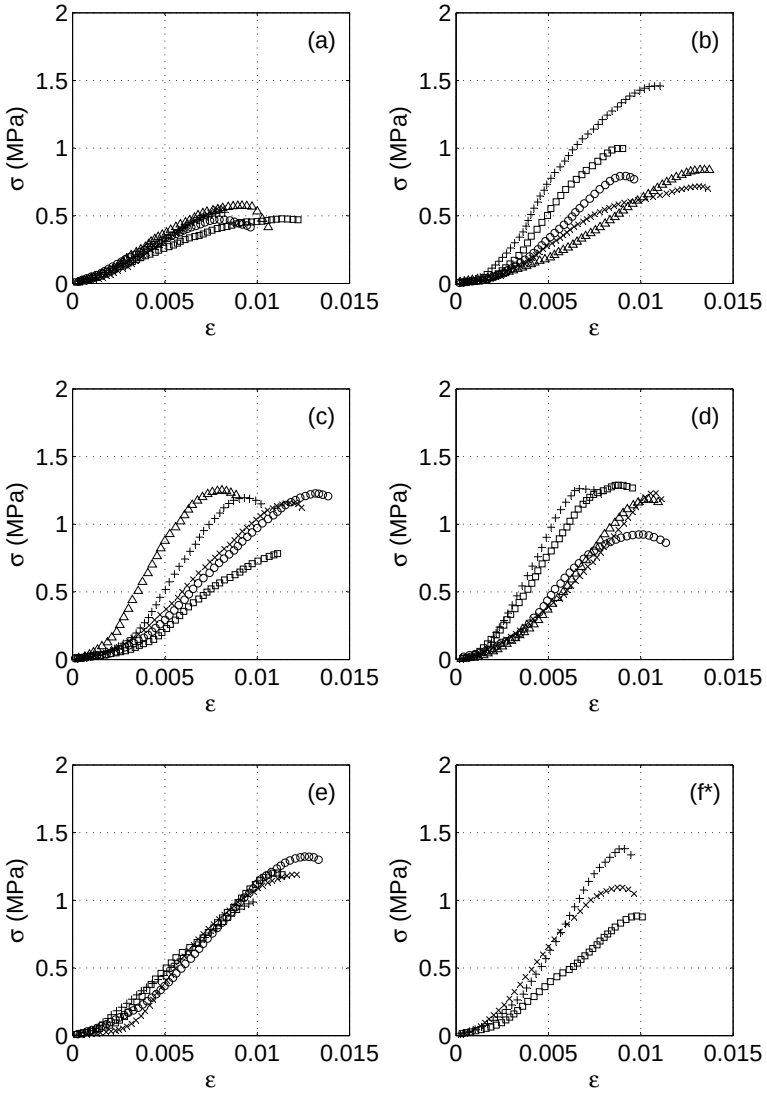


Figure 4: Stress-strain ($\sigma - \varepsilon$) curves for A-series specimens under uniaxial compression at lime contents: a) 0%; b) 2%; c) 3%; d) 4%; e) 5%; f*) 6%. *Please note: due to some damage, only three of the five specimens with 6% lime content were tested.

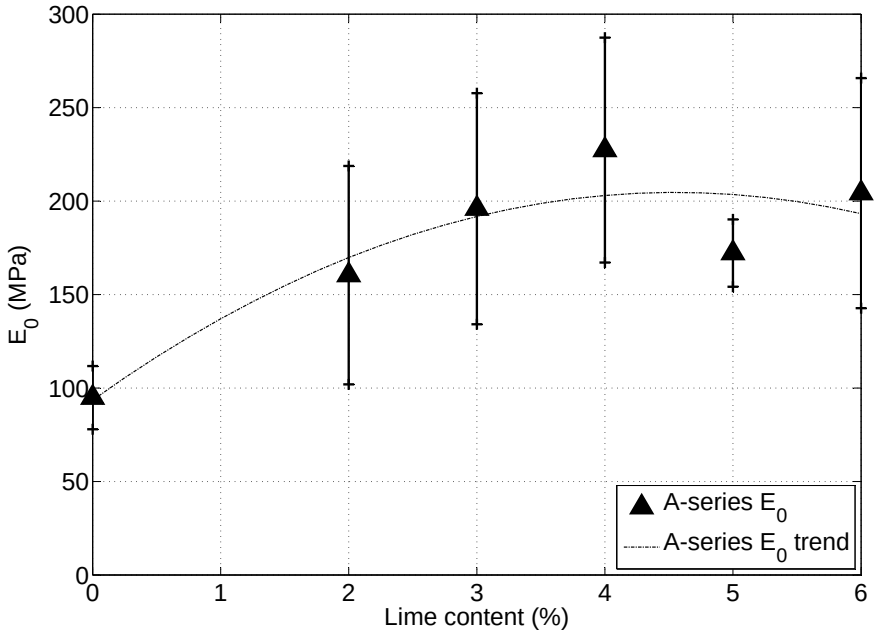


Figure 5: Maximum tangent stiffness modulus results in terms of mean values and standard deviation for (Ambient) A-series specimens.

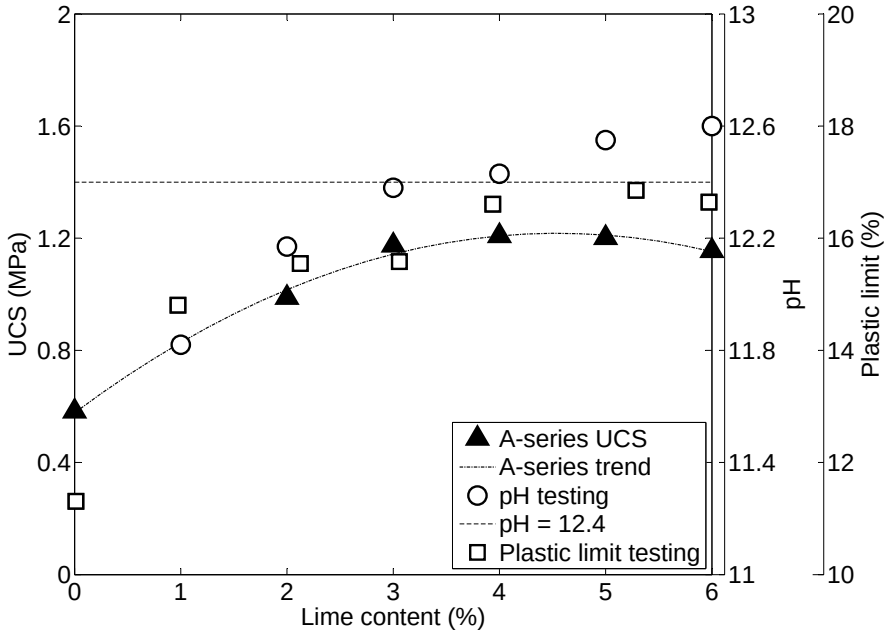


Figure 6: UCS, PL and pH testing results as compared to lime content.

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